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PC[illegible]AU03/00959

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J. Billingsley

JULIE BILLINGSLEY
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<u>SUPPORT AND SALES</u>

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PROVISIONAL SPECIFICATION

Invention Title: Improved multi-channel grating design technique

The invention is described in the following statement:

Improved Multi-Channel Grating Design Technique

Field of the invention

The present invention relates broadly to a method of improving a grating design function describing a refractive index variation defining a multi-channel grating structure in a waveguide material, to a method of fabricating a multi-channel grating structure, and to a multi-channel grating structure.

Background of the invention

Multi-channel grating structures are typically written into photosensitive waveguides. The grating structure comprises a refractive index profile induced in the photosensitive waveguide, which in turn determines the optical characteristics such as the reflection, transmission, and group delay characteristics of the resulting grating structure.

The amplitude and phase of the refractive index profile can be described by a grating design function, which in turn is used in the control of an apparatus for writing the grating structure into the photosensitive waveguide. Typically, the writing apparatus comprises an optical interferometer.

It is known that a maximum refractive index contrast required to write multi-channel gratings increases with increasing number N of channels. Since photosensitive materials, such as a photosensitive fibre used to fabricate a Bragg grating, have material limits of the maximum achievable photo-induced refractive index change Δn, this represents a limitation on the maximum number of channels N that can be recorded in a given material. Thus, it is highly desirable to reduce a required Δn_N as much as possible.

At least preferred embodiments of the present invention seek to provide a method of improving a grating design function in terms of a reduced maximum refractive index variation required in the waveguide material along the grating structure, without compromising the quality of spectral characteristics.

Summary of the invention

In accordance with a first aspect of the present invention there is provided a method of improving a grating design function describing a refractive index variation defining a multi-channel grating structure in a waveguide material, the improvement being a reduced maximum

refractive index variation in the waveguide material along the grating structure while maintaining a desired functional spectral domain in a spectral response function associated with the design function, the method comprising the steps of:

- modifying a first design function to generate a second design function having a reduced maximum amplitude compared with the first design function,

- determining a second response function associated with the second design function,

- modifying the second response function to create a third response function having a desired functional spectral domain, and

- determining a third design function associated with the third response function,

and iterating the method steps until the desired improvement is achieved, wherein the third design function of the previous iteration takes the place of the first design function of the next.

In one embodiment, the step of modifying the second response function comprises replacing the corresponding spectral domain of the second response function by the desired functional spectral domain.

The desired functional spectral domain may comprise a corresponding spectral domain of a first response function associated with the first design function.

The method may comprise the pre-iteration step of determining the first design function from a or the associated first response function.

Preferably, the determining of the response functions from the design functions comprises solving a direct scattering problem, and the determining of the design functions from the response functions comprises solving an inverse scattering problem.

In one embodiment, the third response function further has a desired response characteristic in at least one further spectral domain other than the functional spectral domain.

Preferably, the step of modifying the first design function comprises applying a normalisation process or an averaging process to the first design function.

In one embodiment, the normalising process comprises replacing an amplitude function $\kappa(z)$ of the design function by a product of the square root of a constant A and a corresponding

single-channel seeding amplitude function $\kappa_s(z)$, while maintaining a phase function of the design function. The constant A may be defined by the normalisation condition $A = \int_0^l \kappa^2 dz \,/\, \int_0^l \kappa_s^2 dz$, where l is a length of the multi-channel grating structure.

In one embodiment, the averaging process comprises averaging over a sampling or quasi-sampling period of the design function.

In accordance with a second aspect of the present invention, there is provided a method of fabricating a multi-channel grating structure, the method comprising the step of improving a grating design function describing a refractive index variation defining the multi-channel grating structure in a waveguide material as defined in the first aspect.

In accordance with a third aspect of the present invention, there is provided a multi-channel grating structure fabricated utilising a method of fabrication as defined in the second aspect.

Brief description of the drawings

Preferred forms of the present invention will now be described with reference to the accompanying drawings.

Figures 1 (a)-(d) show calculated the first spectral characteristics and the first design amplitude of a multi-channel grating structure (the first design phase is not shown)

Figures 2 (a)-(d) show calculated the second spectral characteristics and the second design results (normalised/averaged amplitude profile)

Figures 3 (a)-(d) show calculated the third spectral characteristics and the third design results which correspond to the first completed iteration embodying the present invention.

Figures 4 (a)-(d) show calculated spectral characteristics and design results after 8 iterations of an improvement process embodying the present invention.

Figures 5 (a)-(d) show calculated spectral characteristics and design results after 150 iterations of an improvement process embodying the present invention.

Figure 6 is a flowchart illustrating a multi-channel grating design improvement process embodying the present invention.

Figure 7 shows an experimental set-up for writing a multi-channel grating structure of a multi-channel grating design embodying the present invention.

Detailed description of the embodiments

The preferred embodiment described provides a method of improving a grating design function in terms of a reduced maximum refractive index variation required in a waveguide material along the grating structure.

Figures 1(a)-(d) show calculated spectral-characteristics and design of a 17-channel Bragg grating prior to iteration procedure. It will be appreciated by a person skilled in the art that the spectral-characteristics are of a superb quality with virtually no deviations from a desired spectral-characteristics, in the example shown in Figure 1 a square-shaped transmission characteristic (compare Figure 1b).

It has been found by the inventors that the design of the 17-channel Bragg grating shown in Figure 1 can be improved in terms of minimisation of a maximum refractive index change required in the photosensitive material, e.g. a photosensitive optical fibre, into which the 17-channel Bragg grating is to be written. In other words, the fibre Bragg grating (FBG) amplitude versus distance z along the FBG (Figure 1a), can be improved in terms of minimisation of the maximum amplitude without compromising the spectral response. In the example embodiment, this is achieved by subjecting the design to an iterative optimisation procedure which will now be described.

In the example embodiment, the maximum in the FBG amplitude versus distance z is initially reduced in the following way: Starting from the FBG amplitude versus distance z shown in Figure 1(a), the amplitude function $\kappa(z)$ is replaced by $\sqrt{A}\kappa_s(z)$, where $\kappa_s(z)$ is the corresponding single channel (seeding) grating amplitude function and the constant A is defined by the normalisation condition $A = \int_0^l \kappa^2 dz / \int_0^l \kappa_s^2 dz$. Alternatively $\kappa(z)$ is replaced by its averaged (smoothen) version. The unchanged multi-channel grating phase and the modified (the second) grating amplitude are then used as the input data for solving a direct scattering problem utilising a suitable direct scattering solver algorithm. Thus, a spectral response function corresponding to the modified grating design function is determined.

The second grating design amplitude and the corresponding spectral response data are shown in Fig. 2(a-d). Clearly spectral characteristics in the central part of wavelength range, which is the functional spectral domain in the example embodiment, are less than perfect. As a next step these characteristics are modified.

Within the central channel spectral domain it is replaced by the initial (pre-iteration) data, compare Figure 1(b) and 3(b). Outside the central channel spectral domains the determined spectral response data is left intact compare Figure 2(b) and 3(b), i.e. that spectral domain is allowed to evolve during the iteration process.

As a final step of each iteration, an inverse scattering problem is solved for the modified spectral response data to determine the associated, better optimised, multi-channelled grating design function, see Fig. 3(a-d)

The above method steps are then iterated in the example embodiment, until a desired improvement is achieved. Figures 4 and 5 show the level of convergence after 8 and 150 iterations for the 17-channel grating design. For each of the Figures 4 and 5, (a to d) show calculated spectral characteristics and design of the 17-channel FBG. As can be seen from a comparison of Figure 1(a) and Figure 5(e) the optimisation process embodying the present invention has improved by about 13.5% to a lower value, while, due to the nature of the optimisation process embodying the present invention, the superb spectral characteristics of the design (compare Figures 1(b), (d), and Figures 5(b), (d)).

Figure 6 shows a flowchart illustrating the iterative process of the example embodiment, as follows:

Step 500, applying a normalisation or averaging process to a given FBG amplitude function;

Step 502, solve a direct scattering problem based on the modified grating design function;

Step 504, modify the resulting spectral response;

Step 506, solve an inverse scattering problem based on the modified spectral response;

Step 508, determine whether a desired quality has been achieved, and

repeat the steps (return loop 510) if not, or stop the iteration as indicated by arrow 512.

In the following, a description will be given of how to obtain a suitable initial (pre-iteration) grating design (compare Figure 1), in example embodiments.

In the example embodiment, a multi-channel grating function is constructed by solving the standard inverse scattering problem for multi-channel wavelength-shifted spectral characteristics. Spectral response functions $H_R(\lambda)$ for partial single gratings are being de-phased with respect to each other. In other words, the inverse scattering problem may be presented as:

$$H_R^{total}(\lambda) = H_R(\lambda - \lambda_1)e^{i\vartheta_1} + H_R(\lambda - \lambda_2)e^{i\vartheta_2} + H_R(\lambda - \lambda_3)e^{i\vartheta_3} + \ldots \quad (1)$$

with nonzero relative phases ϑ_i in the example embodiment. It is to be noted that spectral responses are being de-phased, not partial seeding gratings themselves. After solving the inverse scattering problem for $H_R^{total}(\lambda)$, the multi-channel grating design function is obtained and may be presented in a form:

$$q(z) = \kappa_s Q e^{i(K_0 z + \theta + \psi)} \equiv \kappa\ e^{i(K_0 z + \theta + \psi)} \quad (2)$$

where we explicitly retain, for illustrative purposes, the single channel grating design function $\kappa_s e^{i(K_0 z + \theta)}$. The remaining factors in the expression (2) represent a "sampling" function, which is aperiodic. It is thus not a sampling, i.e. periodic, function anymore, but deviates from a sampling function.

It will be appreciated by a person skilled in the art that in order to initially (prior to our iterative scheme) pre-optimise the grating design for minimum refractive index change Δn_N as a function of the number of channels N, suitable numerical or analytical methods can be applied.

For relatively small number of channels N one can numerically scan through possible combinations of relative phases ϑ_i (solving an inverse scattering problem for each particular combination of dephasing angles ϑ_i) and selecting the combination which is optimal according to some specific selection criterion (e.g. selecting the combination which minimises maximum required refractive index change).

For $N >> 1$ location of the optimal set ϑ_i is difficult. Even rough direct scanning through all possible sets of angles (followed by efficient numerical minimum search routines) quickly becomes numerically inefficient.

In the example embodiment, the approximate equivalence between partial spectra dephasing angles ϑ_l and partial grating relative phases ϕ_l is utilised. Indeed, for weak gratings the first order Born approximation holds:

$$-\frac{1}{2}q(z/2)=\int_{-\infty}^{+\infty}r(\beta)\exp(-i\beta z)d\beta, \qquad (3)$$

where $q(z)$ is a grating design function and $r(\beta)$ is a complex reflection coefficient.

The Fourier transform (3) is a *linear* operation with a major property $F(a_1\, r^{(1)} + a_2\, r^{(2)}) = a_1\, F\, r^{(1)} + a_2\, F\, r^{(2)}$. Thus, in this approximation, dephasing of partial gratings is equivalent to dephasing of partial spectral channel responses. Formally the last statement does not hold beyond weak grating limit. However, in practice, it is still approximately correct and the optimal set of angles ϕ_l (for dephasing of partial gratings) may be used as a very good approximation for the optimal set of partial spectral channel angles ϑ_l. The only important change related to the "sampling" function between dephasing of partial channels and dephasing of partial gratings approaches is that it becomes slightly aperiodic, as mentioned above.

Therefore, the phase shift values ϑ_l may be taken from a partial gratings de-phasing grating design method. In the example embodiment, a sampling function which periodically modulates the amplitude of a given single-channel grating (seeding grating) is utilised. In addition to the periodic modulation of the amplitude of the seeding grating, different relevant phases ϕ_l for each of the wavelength–seeding gratings are introduced. Accordingly, the resulting design function in the example embodiment may be expressed as:

$$\sum_{l=1}^{N}\kappa_s e^{i[K_0 z+\theta+(2l-N-1)\Delta kz/2+\phi_l]}=\kappa_s Q e^{i(K_0 z+\theta+\psi)}$$

(4)

where the additional phase of the grating $\psi=\psi(z)$ and the sampling amplitude $Q=Q(z)$ are given by:

$$Q^2(z)=4\sum_{l,p=1}^{N/2}\cos(\alpha_l-\alpha_p)\cos(n_l\Delta kz/2+\beta_l)\cos(n_p\Delta kz/2+\beta_p),\text{ and}$$

$$\psi(z) = \tan^{-1}\left[\frac{\sum_{l=1}^{N/2} \sin\alpha_l \cos(n_l \Delta kz/2 + \beta_l)}{\sum_{l=1}^{N/2} \cos\alpha_l \cos(n_l \Delta kz/2 + \beta_l)}\right], \qquad N \text{ is even}$$

or

$$Q^2(z) = 4\sum_{l=1}^{(N-1)/2} \cos\alpha_l \cos(n_l \Delta kz/2 + \beta_l) +$$
$$4\sum_{l,p=1}^{(N-1)/2} \cos(\alpha_l - \alpha_p)\cos(n_l \Delta kz/2 + \beta_l)\cos(n_p \Delta kz/2 + \beta_p) + 1,$$

and

$$\psi(z) = \tan^{-1}\left[\frac{\sum_{l=1}^{(N-1)/2} \sin\alpha_l \cos(n_l \Delta kz/2 + \beta_l)}{\sum_{l=1}^{(N-1)/2} \cos\alpha_l \cos(n_l \Delta kz/2 + \beta_l + 1)}\right], \qquad N \text{ is odd,}$$

where $n_l \equiv 2l - N - 1$ and $n_p \equiv 2p - N - 1$.

In the above expressions for $Q(z)$ and $\psi(z)$ we use notations $\alpha \equiv (\phi_l + \phi_{N+1-l})/2, \beta_l \equiv (\phi_l - \phi_{N+1-l})/2$ and set $\phi_{(N+1)/2} = 0$ for odd number of channels.

In order to reduce the maximum value of Q along the grating structure, while trying to avoid touching the zero level along the grating structure, the minimization strategy used in the example embodiment is minimizing its maximum deviations of $Q(z)$ along z from the theoretical limit level of $\sqrt{N}$. Mathematically this may be formulated as finding $Q_{dm}(z;\alpha_l^{(opt)},\beta_l^{(opt)})$ for which $\begin{matrix}\max_z\{Q_{dm}(z;\alpha_l^{(opt)},\beta_l^{(opt)})\} - \min_z\{Q_{dm}(z;\alpha_l^{(opt)},\beta_l^{(opt)})\} = \\ \min_{(\alpha_l,\beta_l)}[\max_z\{Q(z;\alpha_l,\beta_l)\} - \min_z\{Q(z;\alpha_l,\beta_l)\}]\end{matrix}$

This approach is implemented in the example embodiment by using a simulated annealing algorithm - a Monte Carlo approach for minimizing of multi-variable functions.

The phase shift values ϕ_l $\left(\alpha_l^{(opt)}, \beta_l^{(opt)}\right)$ thus determined are then utilised as phase shift values ϑ_i for the inverse scattering problem as part of the example embodiment (see equation (1)). The obtained dephased N-channel design may be used as an input for the iterative optimisation procedure embodying the present invention.

In the preferred embodiment, the strategy of difference minimisation is then extended further. The N-central-channel-only minimisation set of dephasing angles ϕ_i $(1 < i < N)$ is taken

and used to construct the initial sampling function $S(z) = Q(z)\, e^{i\psi(z)}$ on a period $2\pi/\Delta k$. Then the nontrivial $Q(z)$ dependence is replaced by the asymptotic value $N^{1/2}$ and the resulting intermediate sampling function (with only phase sampling present) is decomposed in a Fourier series to find new Fourier coefficients a_l and a new set of the corresponding dephasing angles $\phi_l \equiv \mathrm{Arg}(a_l)$. This procedure leads to a change in partial high-amplitude grating coefficients. In addition, n extra small higher order harmonic terms (corresponding to additional small amplitude partial gratings) arise. Next we replace coefficients a_l for N high-amplitude partial gratings with $Ce^{i\psi_l^{(new)}}$, where a constant C is found from the normalisation condition

$$\sum_{l=1}^{N} |a_l|^2 = NC^2 \tag{4}$$

and all coefficients a_l outside the band $l \in [1 - n/2, N + n/2]$ being set to zero. These modified $N+n$ amplitudes are used to construct a new "sampling" function via inverse Fourier transformation.

The procedure is repeated until a selected quality criterion has been reached. In the example embodiment, the iteration is stopped when a variation in the maximum "sampling" function amplitude between iterations falls below 10^{-6}.

The extended dephasing procedure for an infinite number of side channels n translates *all* nontrivial amplitude modulation of the sampling function into its phase $\psi(z)$. As a price for doing that, about $10N$ additional partial gratings (higher order harmonics with $|a_l| > 0.001$) appear in the spectral characteristics, which means that phase dependence $\psi(z)$ has a very fine structure. However, for practical applications the scale of the fine structure should always be larger than the size of the laser beam used for grating writing. An estimate for the upper limit for the maximum number $N+n$ of nonzero partial gratings can be given as

$$N + n = \frac{125\lambda_0^2}{z_0 \Delta\lambda_0 n_0}, \tag{5}$$

where λ_0 is the central wavelength [in microns], z_0 is the minimal laser beam size [in microns], $\Delta\lambda$ is the neighbouring channel spacing [in nanometers], and n_0 is the FBG average refractive index. Estimate (5) was obtained using the assumption that about 8 grid points describe a period of the function cos(z) well enough. For the purpose of this description, the upper limit for the maximum number $N+n$ given by the resolution limitation in the fabrication

of the grating [estimate (5)] will be referred to as un-limited in the context of the preferred embodiment of the present invention, as it relates to a given experimental limitation.

In the example embodiment, the number of additional small amplitude partial gratings has been (further) limited. It was found that selecting $n=2N+2$ channels gives good results in preferred embodiments of the invention.

Accordingly, in the example embodiment the initial (pre-iteration) grating design function (compare Figure 1) is arrived at through a multi-channel grating design approach based on partial single grating dephasing, which may be further modified by an extended grating dephasing procedure allowing for a limited number of side channels in the spectral characteristics. The set of angles and amplitudes obtained by the grating dephasing procedure is used for spectral dephasing of partial channels to obtain a pre-iteration design. After this pre-iteration design is obtained, the iterative procedure embodying the present invention is applied.

The implementation of the multi-channel grating design of the preferred embodiment in a grating structure requires grating writing apparatus with high spatial resolution to be utilised. Therefore, in a grating writing apparatus relying on photo induced refractive index changes, the apparatus preferably comprises a beam focusing means to reduce the size of the beam in the core of the photosensitive waveguide.

Figure 7 shows an example experimental set up 50 for writing a multi-channel grating 52 into an optical fibre 54. The experimental set up 50 comprises an interferometer 56 which includes a first acousto-optic modulation 58 being operated under an acousto-optic wave of a first frequency Ω_1, as indicated by arrow 14. An incoming light beam 60 is incident on the first acousto-optic modulator 58 under a first order Bragg angle. The operating conditions of the acousto-optic modulator 58 are chosen such that the modulator 58 is under driven, whereby approximately 50% of the incoming beam 60 is diffracted into a first order beam 62, and 50% passing through the acousto-optic modulator 58 as un-diffracted beam 64. The un-diffracted beam 64 is incident on a second acousto-optic modulator 66 of the interferometer 56 under a first order Bragg angle, whereas the beam 62 is not. Accordingly, the beam 62 passing through the second acousto-optic modulator 66 without any significant loss.

The second acousto-optic modulator 66 is operated under an acousto-optic wave of a frequency Ω_2, which propagates in a direction opposed the direction of the acousto-optic wave in the first modulator 58 as indicated by arrow 68. After the second acousto-optic modulator 66

the first order diffracted beam 70 and the beam 62 are frequency shifted in the same direction (e.g. higher frequency), but by different amounts i.e. Ω_1 v Ω_2.

The beams 62, 70 are then brought to interference utilising an optical lens 72, and the resulting interference pattern (at numeral 74) induces refractive index changes in the photosensitive optical fibre 54, whereby a refractive index profile, i.e. grating structure 52, is created in the optical fibre 54.

In Figure 7, the optical fibre 54 is translated along the interferometer at a speed v, as indicated by arrow 74.

It will be appreciated by a person skilled in the art that the experimental set up 50 shown in Figure 7 can be utilised to write a multi-channel grating structure of a multi-channel grating design embodying the present invention through suitable control of the first and second acousto-optic modulators 58, 66, in conjunction with a suitable control of the speed v at which the optical fibre 54 is translated along the interferometer 56 at any particular time. The high spatial resolution required to implement the multi-channel design of the preferred embodiment is achieved in the set up shown in Figure 7 by utilising optical lens 72, with the practical limit of the beam size in the focal plane preferably being of the order of the waveguide core size.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit of scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

For example, it will be appreciated that the initial grating design function utilised as the starting point of an improvement method embodying the present invention may be derived utilising different methods as the ones described for the example embodiment. Alternative methods can be found e.g. in Patent Co-operation Treaty (PCT) patent application no. PCT/AU02/00160 filed on 15 February 2002, entitled "Multi-channel grating design" assigned to the present applicant, PCT application no. PCT/AU02/00309 filed on 15 March 2002, entitled "Grating design" assigned to the present applicant, and/or Australian provisional patent application no. PS1131 filed on 15 March 2002, entitled "Improved multi-channel grating design" in the name of the present applicant.

Furthermore, it will be appreciated that the present invention is not limited to the type of multi-channel gratings of the example embodiments described. For example, the present invention can be equally applied to multi-channel gratings consisting of non-identical spectral channels, and/or gratings consisting of groups of spectral channels.

Furthermore, it will be appreciated that other numerical or mathematical approaches can be taken to implement the iterative procedure embodying the present invention, e.g. comprises solving complex integral equations.

Furthermore, multi-channel gratings can be created on the basis of the multi-channel grating design of the present invention using various known grating creation techniques, including one or more of the group of photo-induced refractive index variation in photo sensitive waveguide materials, etching techniques including etching techniques utilising a phasemask, and epitaxial techniques.

In the claims that follow and in the summary of the invention, except where the context requires otherwise due to express language or necessary implication the word “comprising” is used in the sense of “including”, i.e. the features specified may be associated with further features in various embodiments of the invention.

Claims

1. A method of improving a grating design function describing a refractive index variation defining a multi-channel grating structure in a waveguide material, the improvement being a reduced maximum refractive index variation in the waveguide material along the grating structure while maintaining a desired functional spectral domain in a spectral response function associated with the design function, the method comprising the steps of:

- modifying a first design function to generate a second design function having a reduced maximum amplitude compared with the first design function,

- determining a second response function associated with the second design function,

- modifying the second response function to create a third response function having a desired functional spectral domain, and

- determining a third design function associated with the third response function,

and iterating the method steps until the desired improvement is achieved, wherein the third design function of the previous iteration takes the place of the first design function of the next.

2. A method as claimed in claim 1, wherein the step of modifying the second response function comprises replacing the corresponding spectral domain of the second response function by the desired functional spectral domain.

3. A method as claimed in claims 1 or 2, wherein the desired functional spectral domain comprises a corresponding spectral domain of a first response function associated with the first design function.

4. A method as claimed in any one of the preceding claims, wherein the method comprises the pre-iteration step of determining the first design function from a or the associated first response function.

5. A method as claimed in any one of the preceding claims, wherein the determining of the response functions from the design functions comprises solving a direct scattering problem, and the determining of the design functions from the response functions comprises solving an inverse scattering problem.

6. A method as claimed in any one of the preceding claims, wherein the third response function further has a desired response characteristic in at least one further spectral domain other than the functional spectral domain.

7. A method as claimed in any one of the preceding claims, wherein the step of modifying the first design function comprises applying a normalisation process or an averaging process to the first design function.

8. A method as claimed in claim 7, wherein the normalising process comprises replacing an amplitude function $\kappa(z)$ of the design function by a product of the square root of a constant A and a corresponding single-channel seeding amplitude function $\kappa_s(z)$, while maintaining a phase function of the design function.

9. A method as claimed in claim 8, wherein the constant A is defined by the normalisation condition $A = \int_0^l \kappa^2 dz / \int_0^l \kappa_s^2 dz$, where l is a length of the multi-channel grating structure.

10. A method as claimed in claim 7, wherein the averaging process comprises averaging over a sampling or quasi-sampling period of the design function.

11. A method of fabricating a multi-channel grating structure, the method comprising the step of improving a grating design function describing a refractive index variation defining the multi-channel grating structure in a waveguide material as claimed in any one of the preceding claims.

12. A multi-channel grating structure fabricated utilising a method of fabrication as claimed in any one of the preceding claims.

Dated this 30th day of July 2002

Redfern Optical Components Pty Ltd

by its attorneys

Freehills Carter Smith Beadle

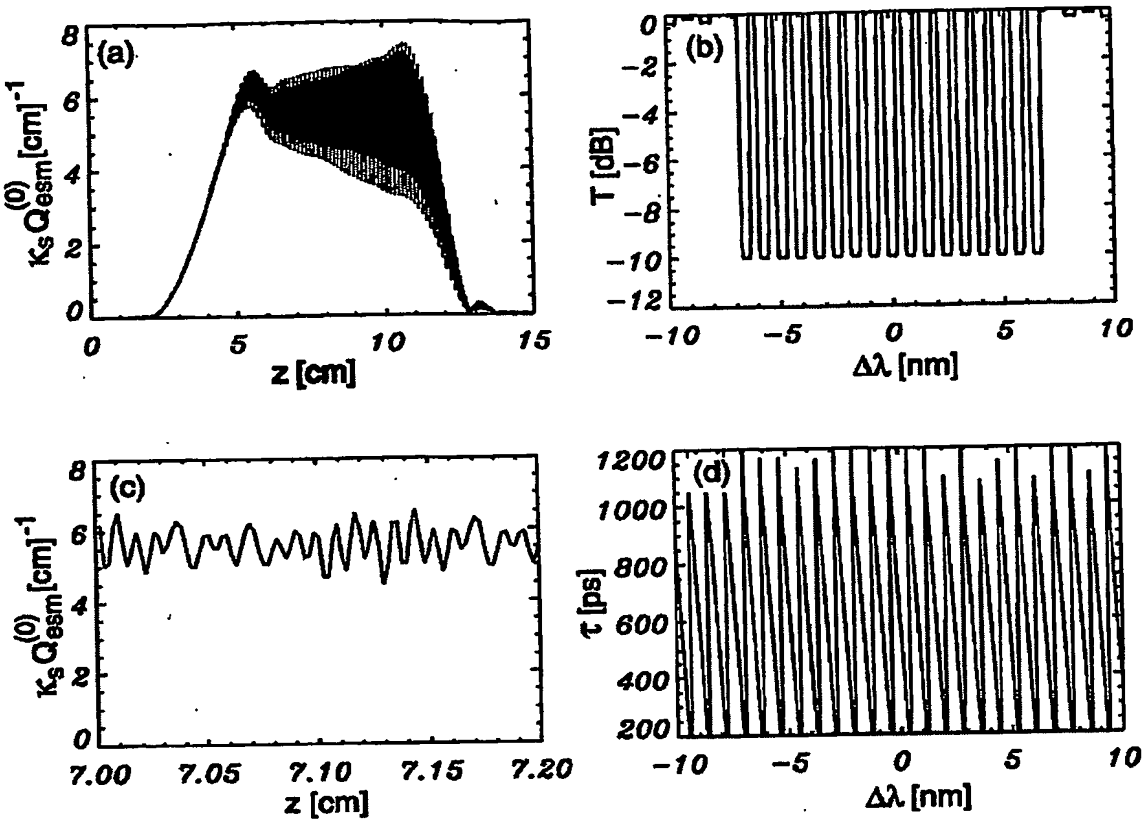
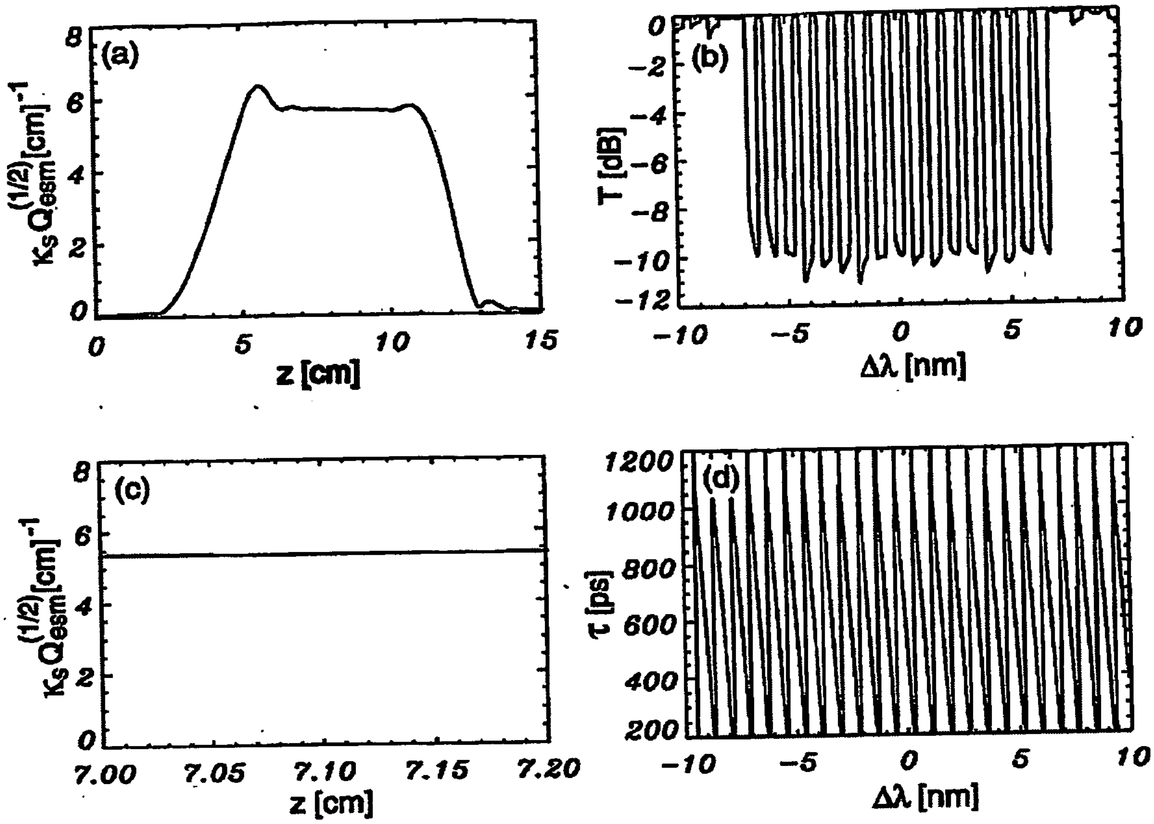


FIG. 1


(a)
(b)
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0
2
4
6
8
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10
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−2
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−8
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400
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800
1000
1200

FIG. 2

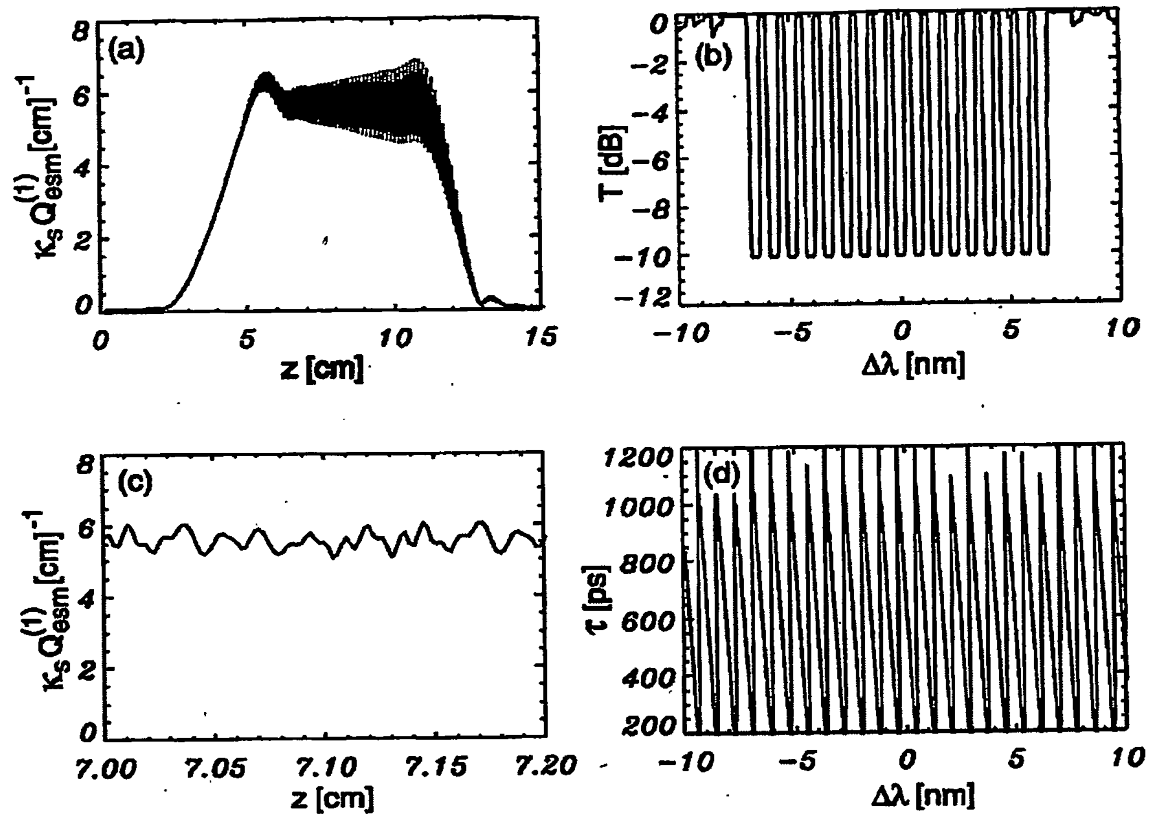


FIG. 3

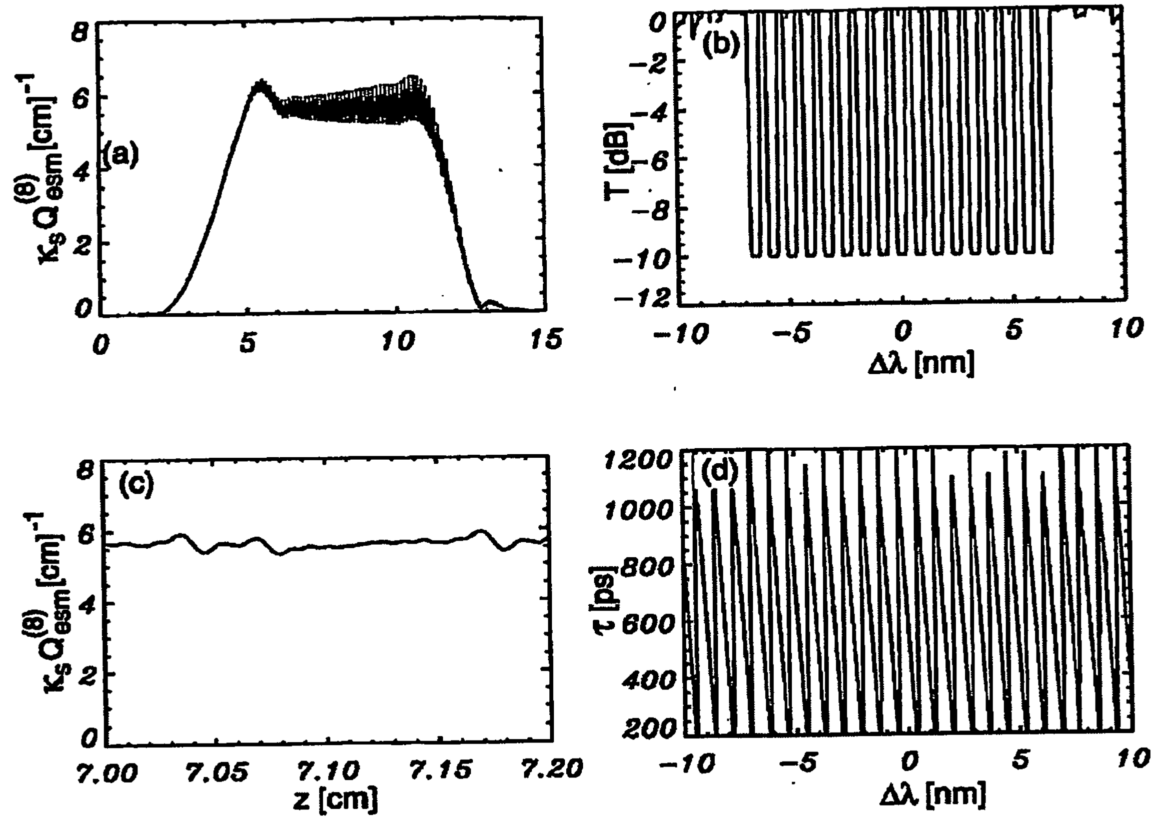
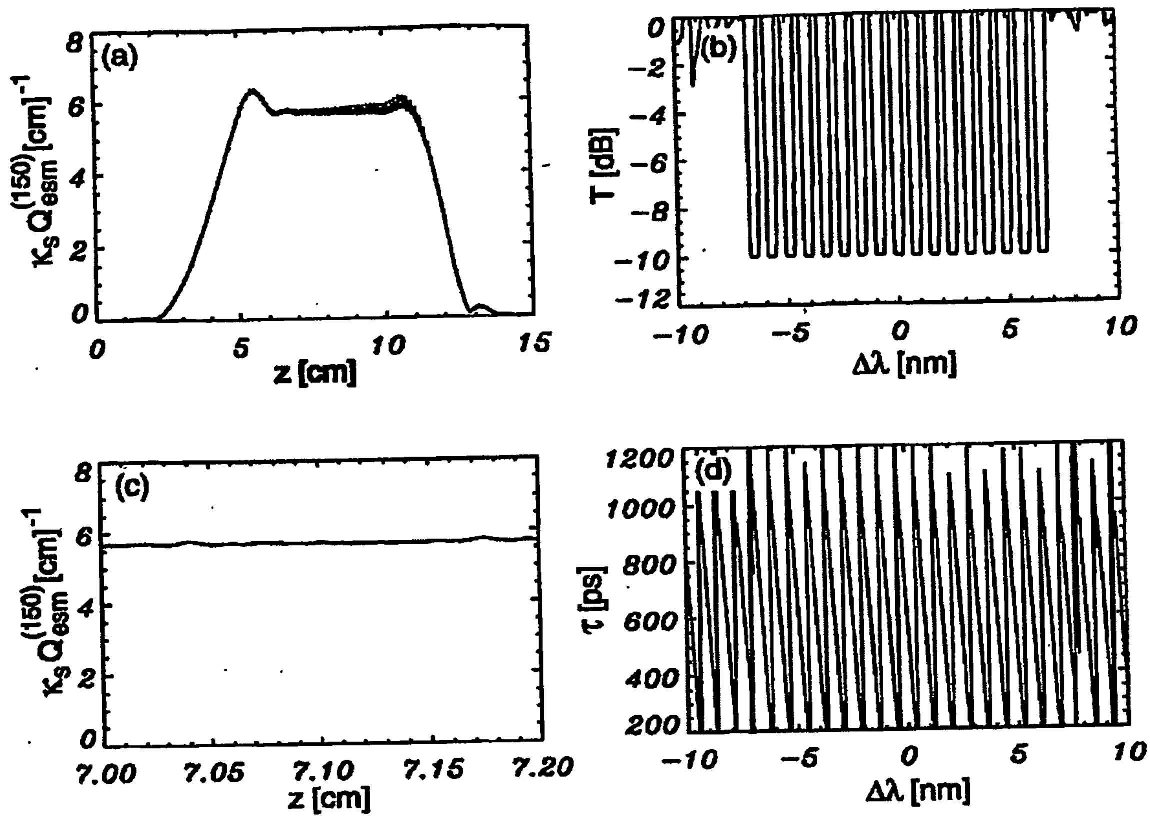


FIG. 4


(a)
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z [cm]
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0
5
10
15
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7.00
7.05
7.10
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1000
1200

FIG. 5

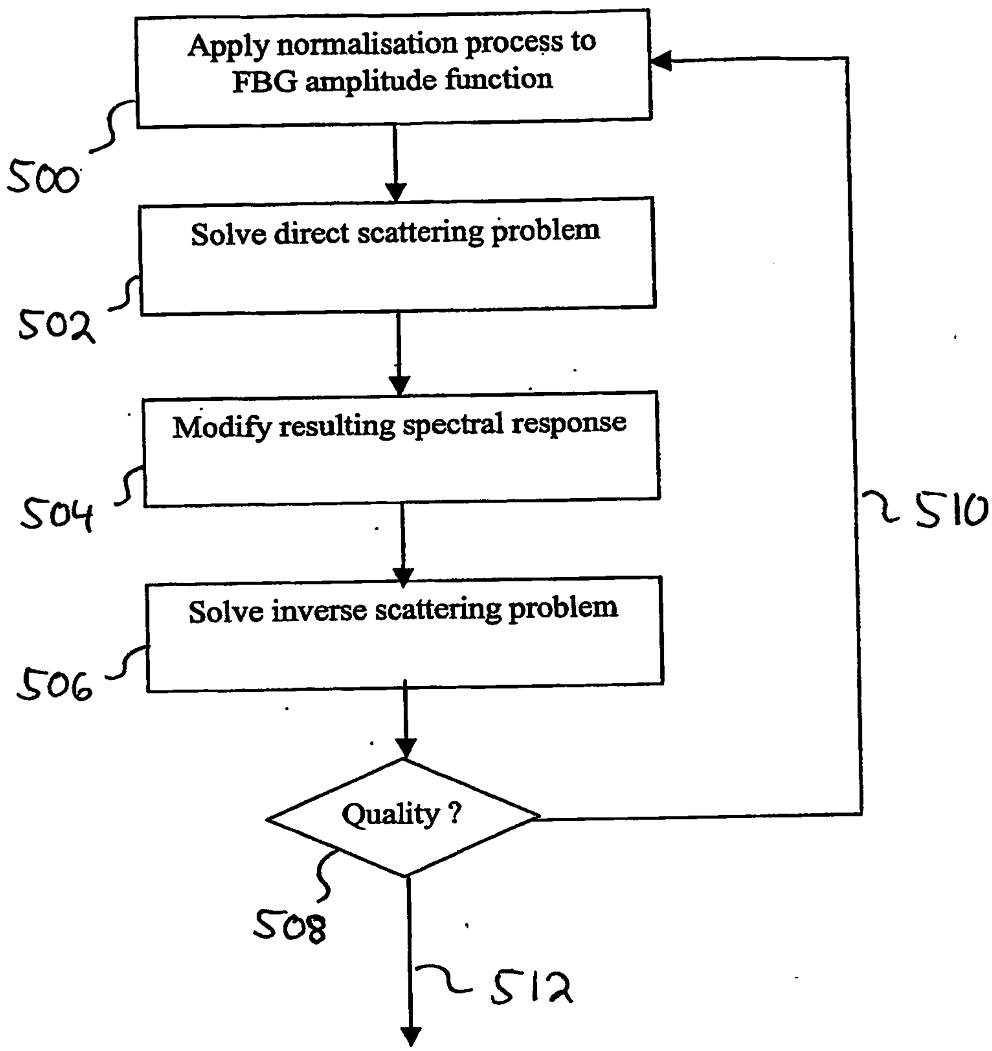
Apply normalisation process to FBG amplitude function
500
Solve direct scattering problem
502
Modify resulting spectral response
504
Solve inverse scattering problem
506
Quality ?
508
510
512

FIG. 6

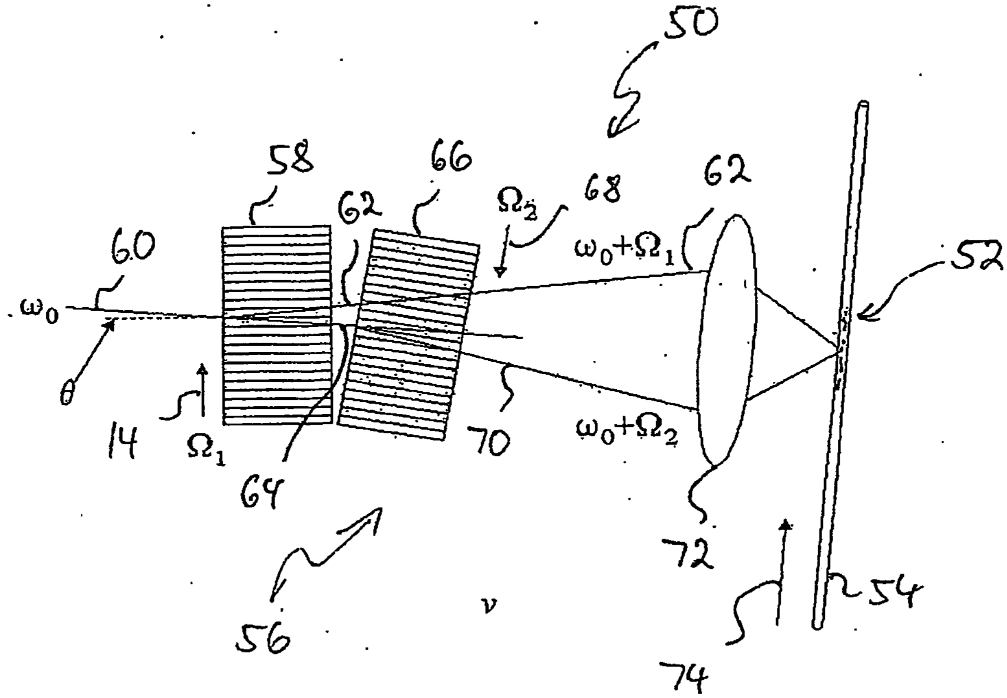
50
58
66
62
Ω_2
68
62
60
$\omega_0+\Omega_1$
52
ω_0
θ
14
Ω_1
64
70
$\omega_0+\Omega_2$
72
56
54
74

FIG. 7